Real time SWE mapping in the Sierra Nevada using snow sensor data, models, airborne and satellite data

Noah Molotch

Geography / INSTAAR, University of Colorado

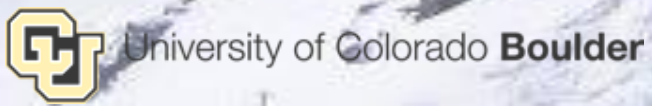
Jet Propulsion Laboratory, California Institute of Technology

CCSS

11/15/2018

Leanne Lestak, Keith Musselman, Lauren Tomkinson

Kehan Yang, ASO team

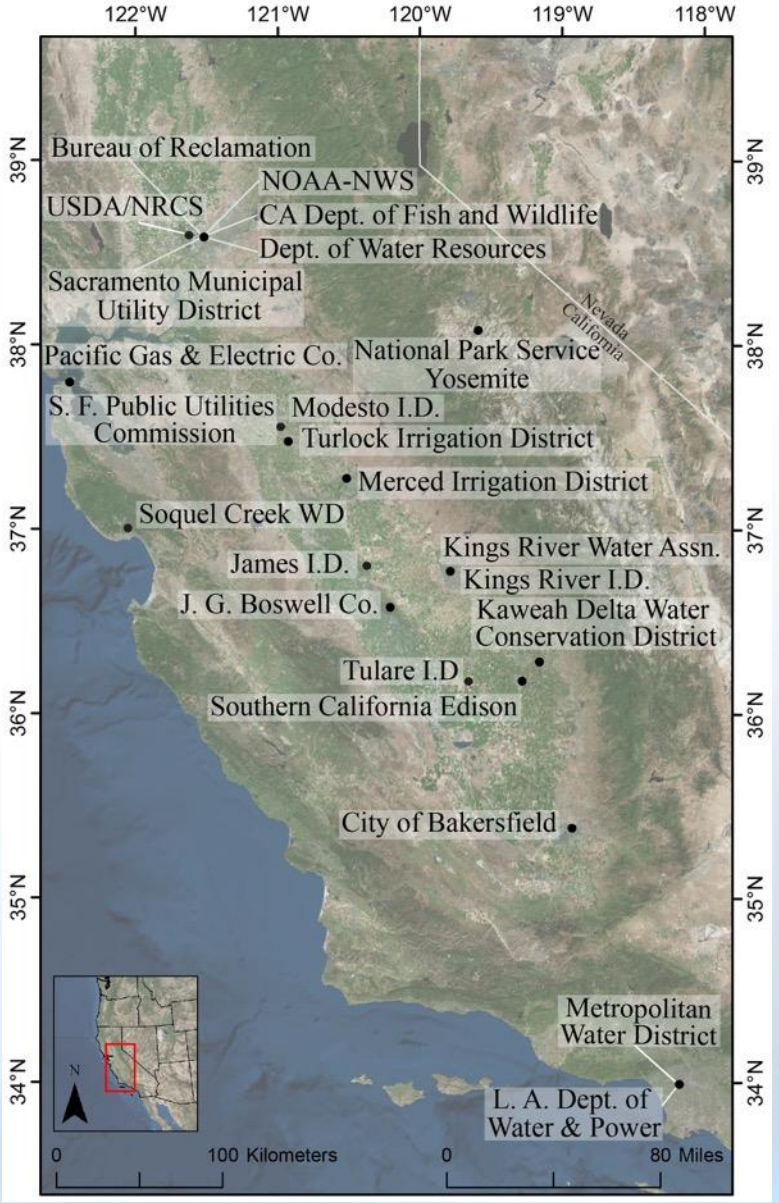


Integrated Real-Time SWE Mapping

Current partners and user community

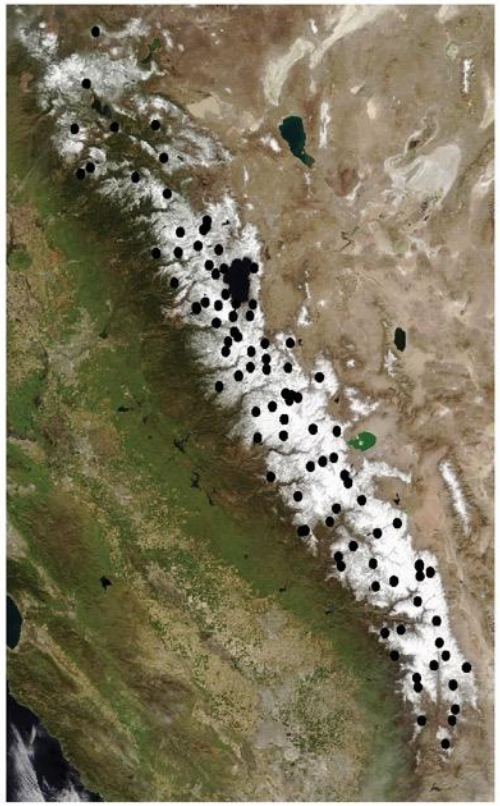
- Partner: California Dept of Water Resources
- Center for Water, Earth Science & Technology
- JPL
- User community: Federal, state and local entities across California; e.g. irrigation districts and municipalities.

University of Colorado Boulder

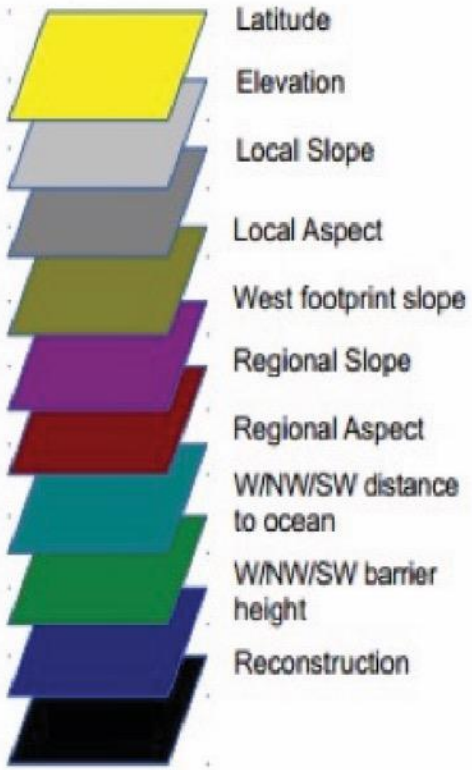


Linear Regression Model (LRM) SWE

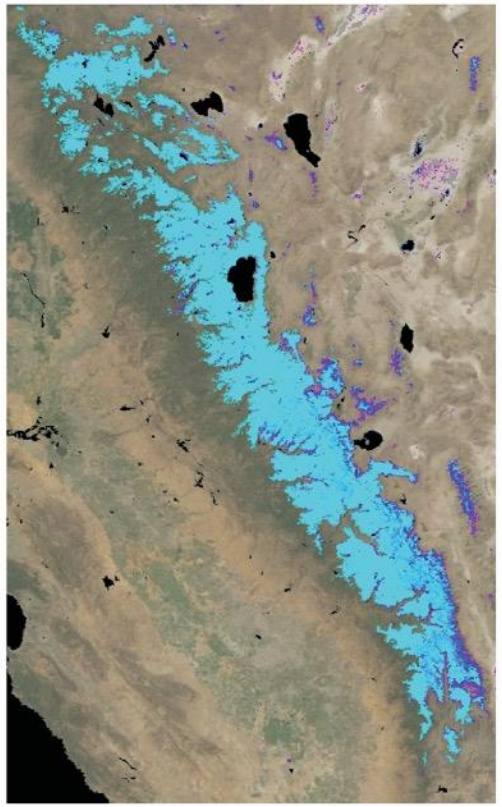
Snow Pillows



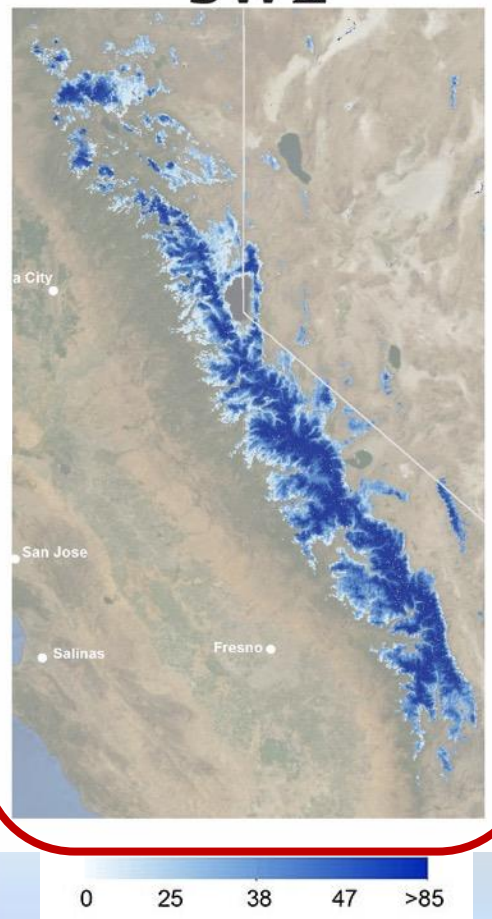
Independent Variables



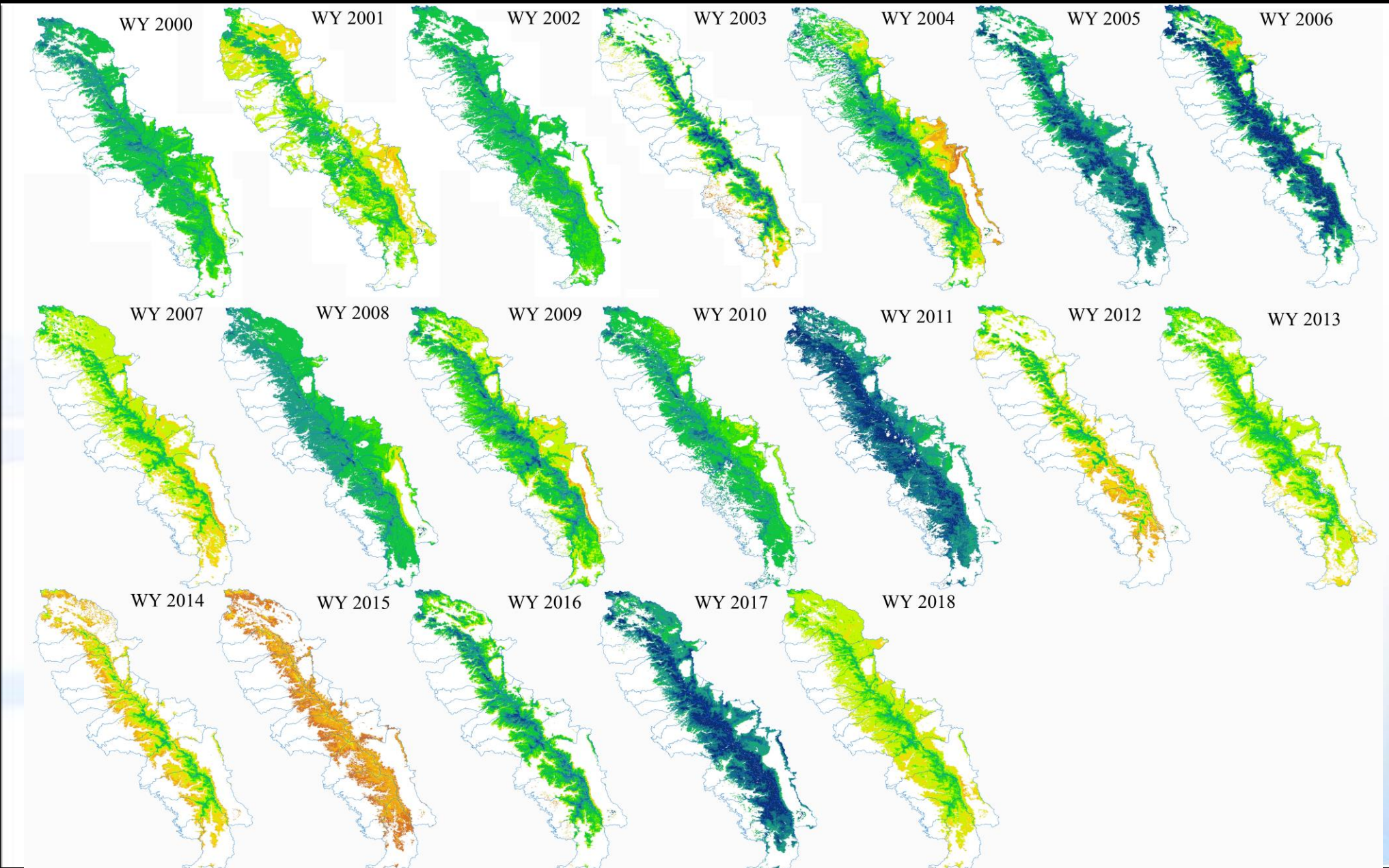
MODSCAG Snow-covered Area

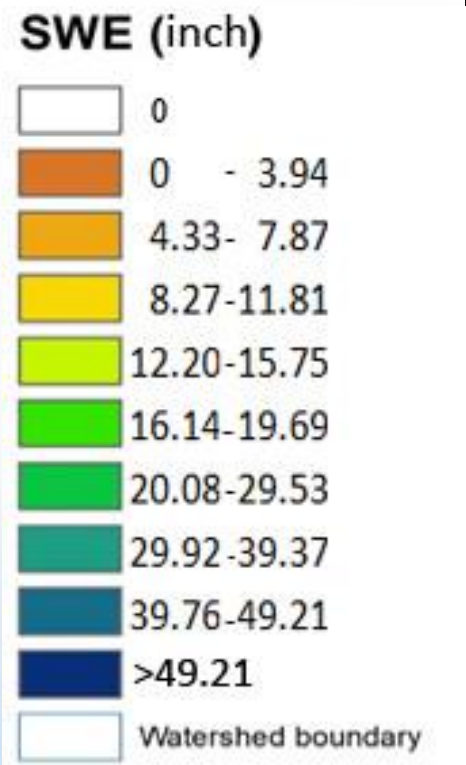


Regression SWE

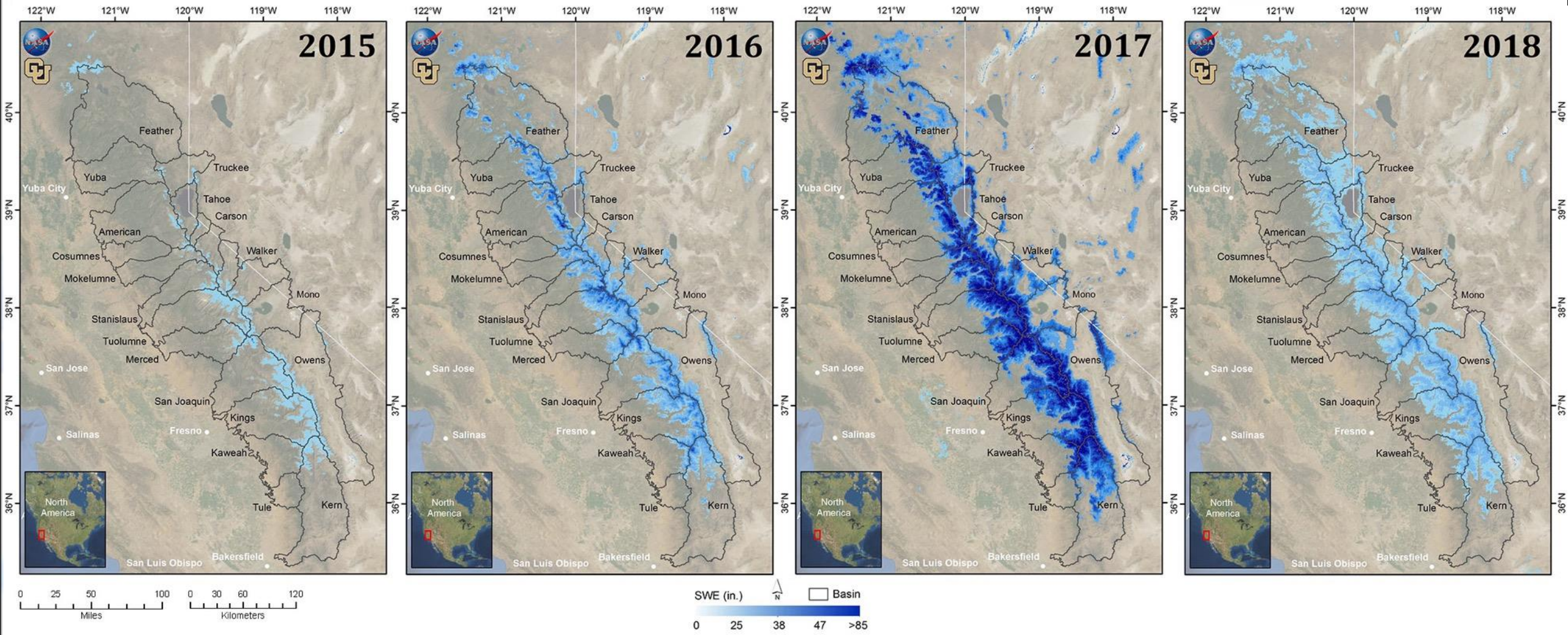


Linear Regression Model (LRM)SWE: 2000 - 2018

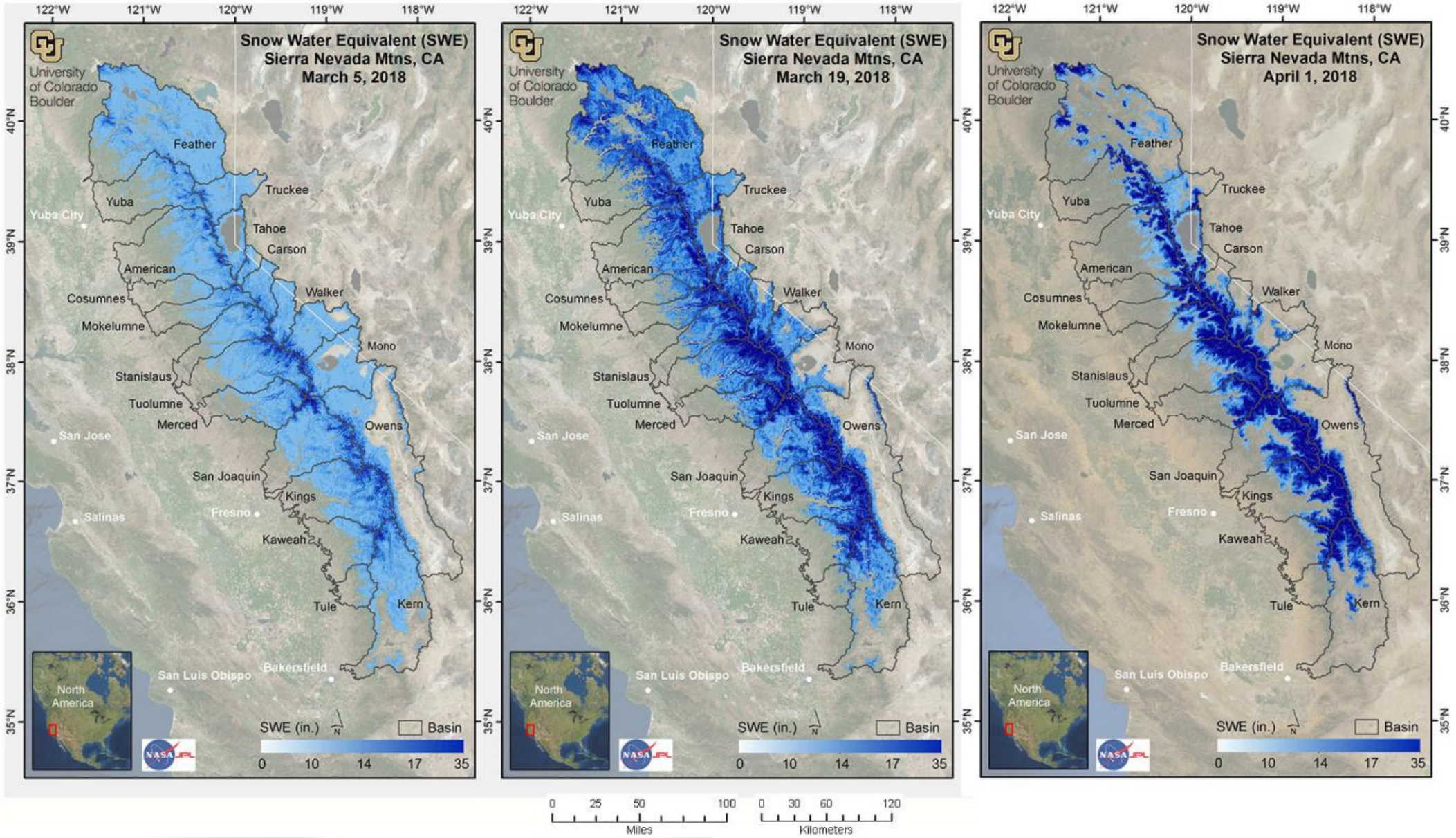




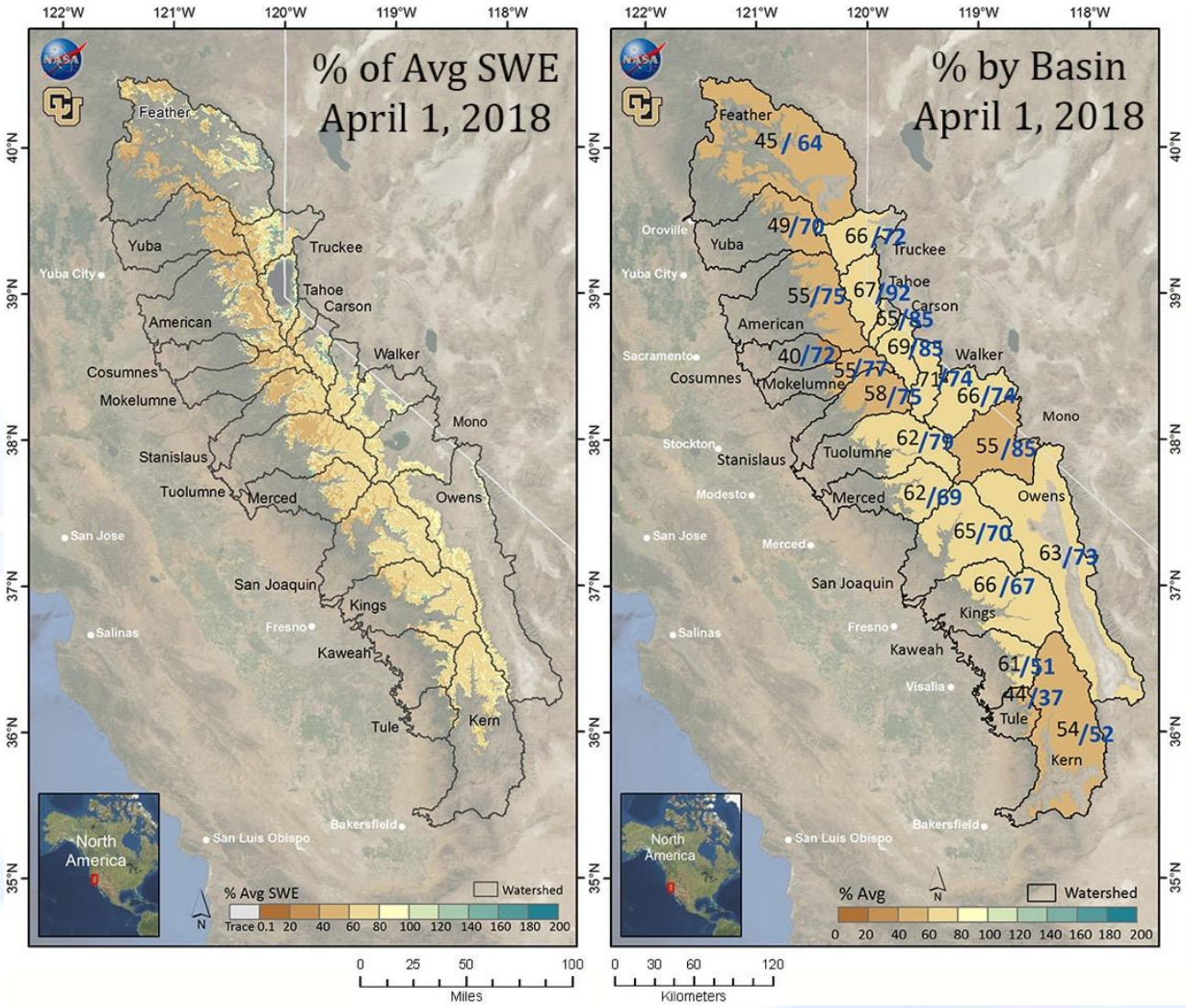
Recent inter-annual variability of April 1st SWE



Real-time SWE Report Example: April 1, 2018



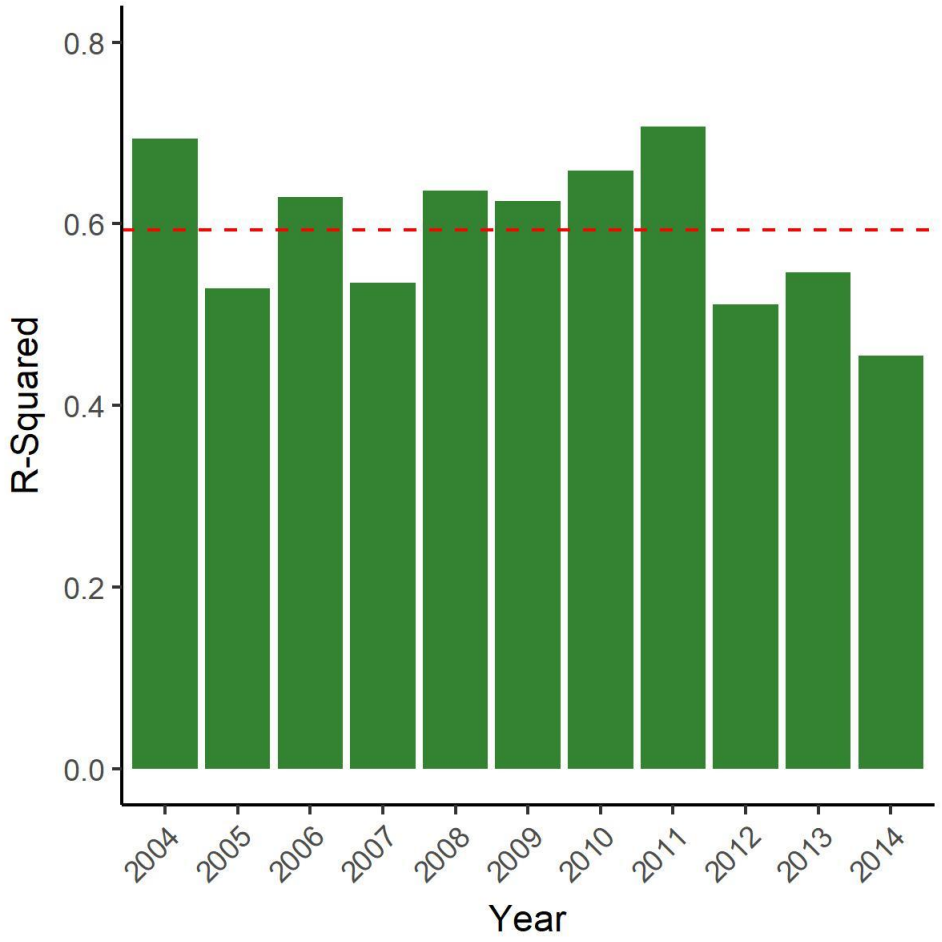
Real-time SWE Report Example: Apr 1, 2018



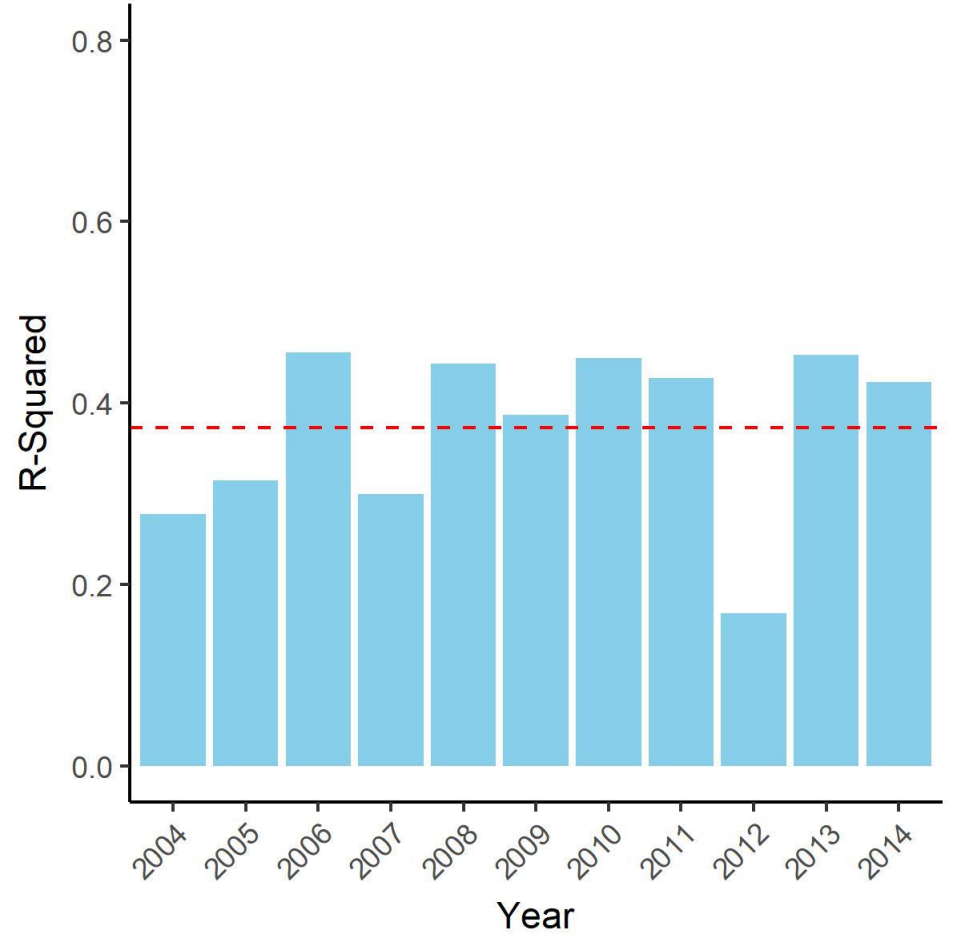
Basin	Elevation Band	3/19/18 % 3/19 Avg.	4/1/18 % 4/1 Avg.	4/1/18 SNODAS (in)	3/19/18 SWE (in)	4/1/18 SWE (in)	3/19 thru 4/1/18 Chg. in SWE (in)	Area Sq Mi
American	5000-6000'	97	49	9.3	13.3	6.1	-7.2	295.5
	6000-7000'	56	52	12.9	14.4	12.6	-1.8	261.0
	7000-8000'	53	57	18.2	17.2	19.0	1.9	166.3
	8000-9000'	58	63	26.7	21.1	24.6	3.5	67.8
	9000-10,000'	58	65	32.7	24.4	29.5	5.2	8.6
Cosumnes	5000-6000'	162	23	2.8	10.9	2.1	-8.8	57.9
	6000-7000'	67	54	5.4	13.7	10.1	-3.6	22.9
	7000-8000'	50	52	8.2	15.0	15.5	0.5	6.4
E. Carson	5000-6000'	-	2	0.0	9.5	0.0	-9.5	65.9
	6000-7000'	129	57	0.4	13.3	3.2	-10.0	90.7
	7000-8000'	71	73	6.2	14.2	11.7	-2.5	104.8
	8000-9000'	60	68	16.5	16.0	17.7	1.7	95.2
	9000-10,000'	64	73	24.8	19.1	22.3	3.2	33.8
	10,000-11,000'	65	76	29.1	20.6	24.8	4.2	10.3
	> 11,000'	59	72	22.4	21.1	27.5	6.5	0.3
E. Walker	5000-6000'	0	6	0.0	0.0	0.0	0.0	21.5
	6000-7000'	107	36	0.0	2.7	0.1	-2.7	211.7
	7000-8000'	72	74	0.1	7.7	2.1	-5.5	254.4
	8000-9000'	66	76	1.9	12.1	9.9	-2.2	185.8
	9000-10,000'	64	75	10.4	15.6	17.4	1.8	76.6
	10,000-11,000'	63	76	14.2	19.8	23.8	4.0	40.6
	11,000-12,000'	62	76	8.8	20.2	25.6	5.4	10.3
	> 12,000'	62	31	6.5	20.9	26.9	6.0	0.3
Feather	5000-6000'	101	55	3.4	13.5	3.3	-10.2	1,259.3
	6000-7000'	68	61	5.8	15.0	10.2	-4.7	706.5
	7000-8000'	57	67	11.6	16.7	17.1	0.4	114.3
	8000-9000'	61	0	19.4	21.1	23.9	2.8	3.7
Kaweah	5000-6000'	80	14	0.1	1.9	0.0	-1.9	62.1
	6000-7000'	107	54	2.0	8.3	0.8	-7.5	59.5
	7000-8000'	79	67	5.5	11.7	7.3	-4.4	58.6
	8000-9000'	64	70	11.2	13.4	14.7	1.3	55.6

Correlation of SWE products with snow course data

LRM mean: 0.59

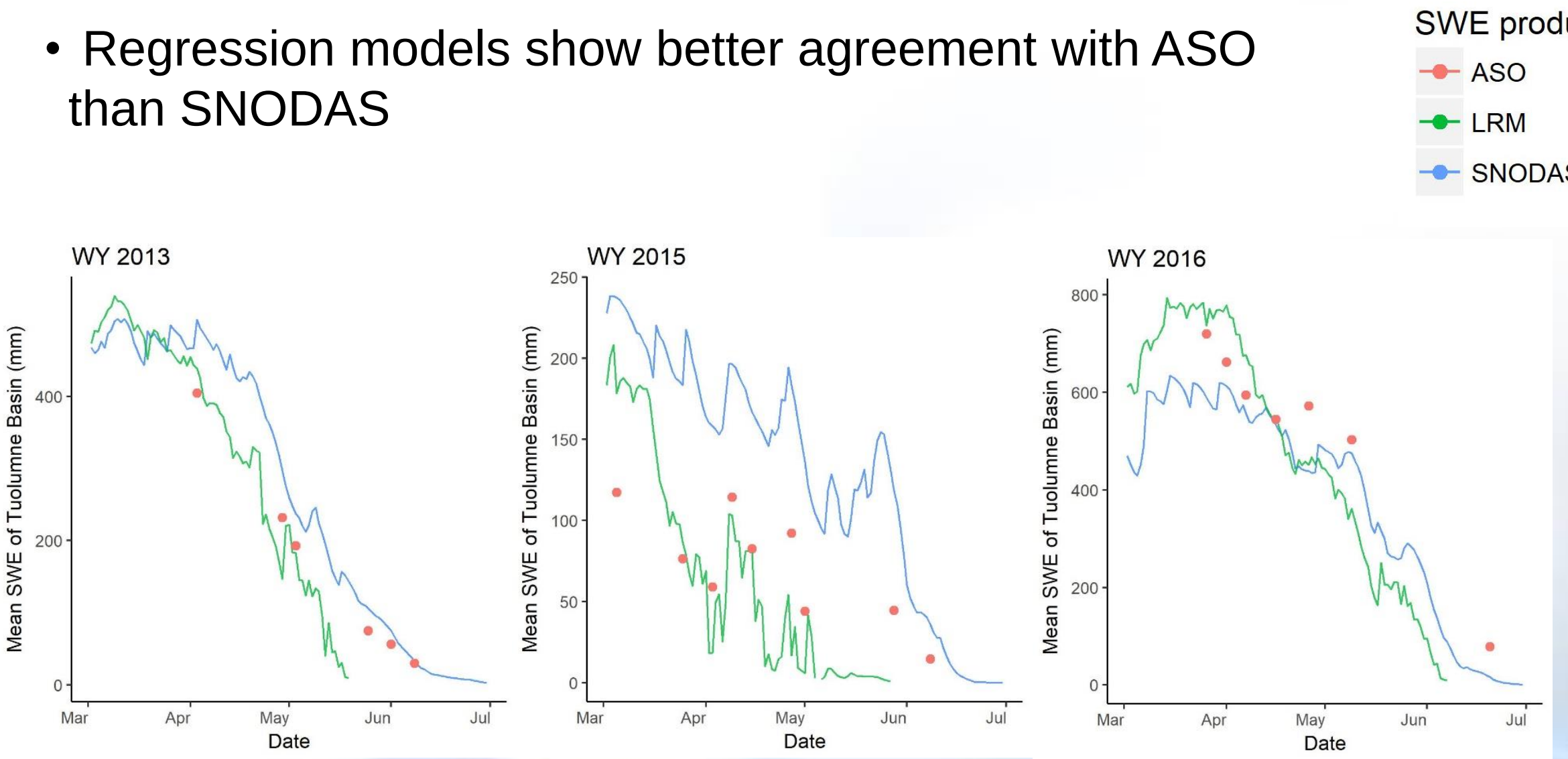


SNODAS mean: 0.37



Avg SWE Tuolumne Basin – Comparison w/ ASO

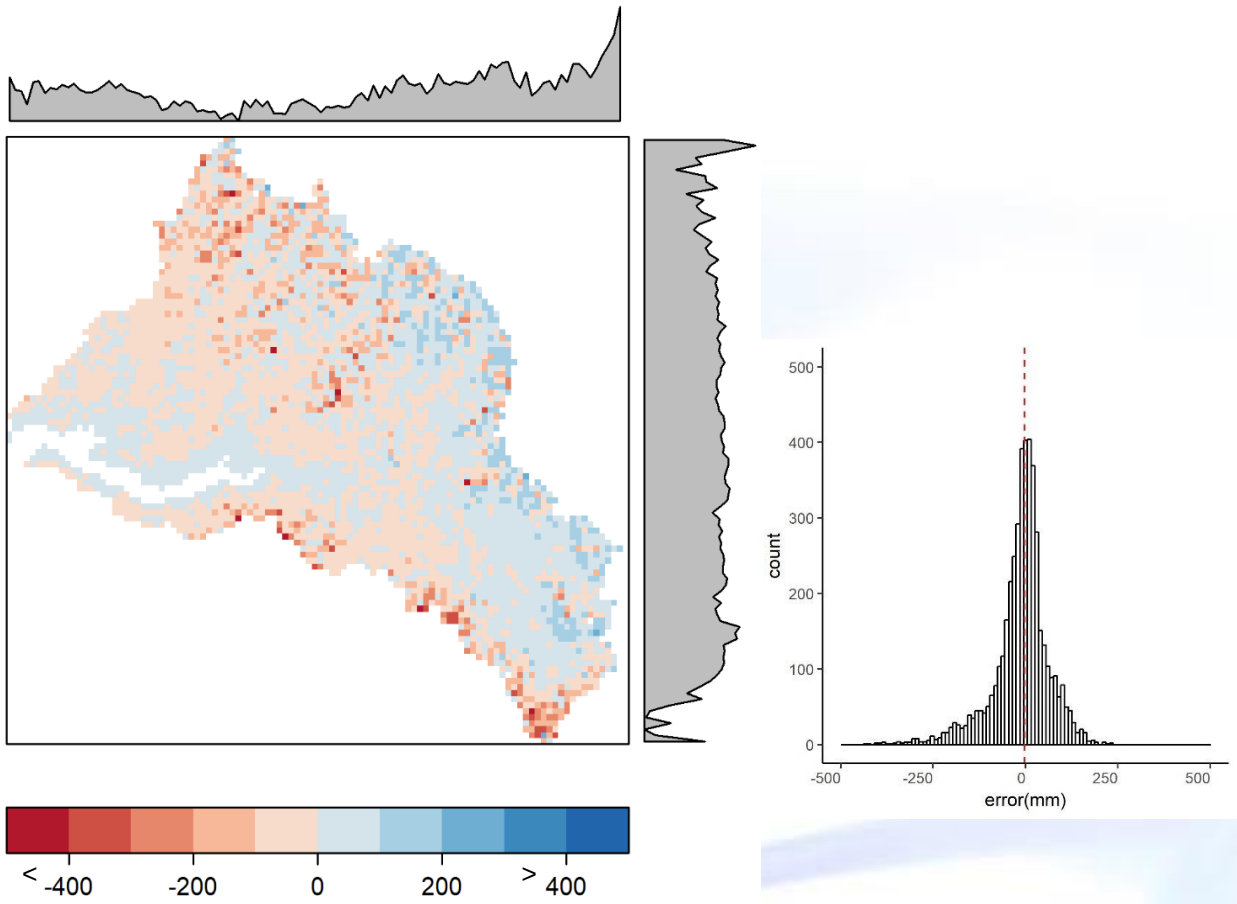
- Regression models show better agreement with ASO than SNODAS



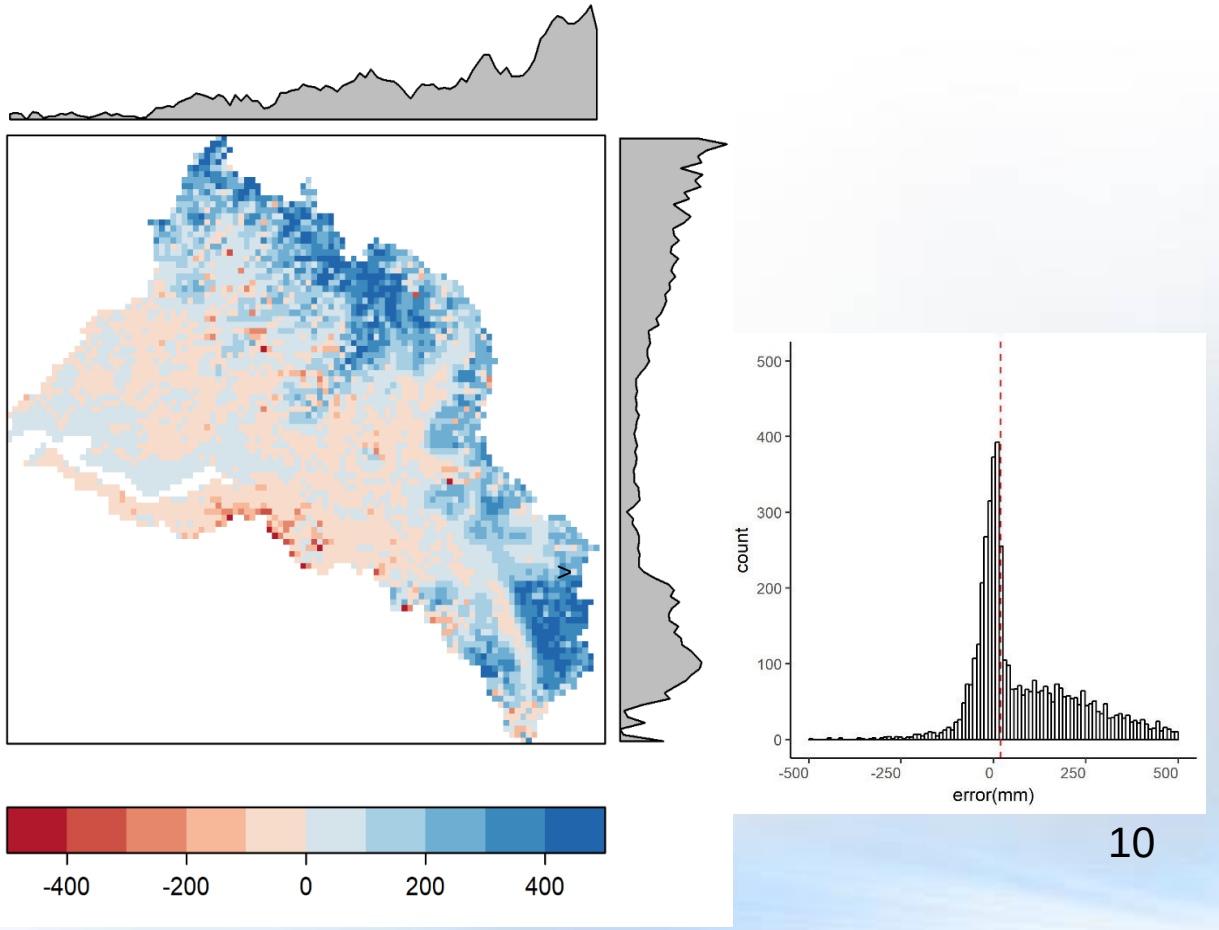
Difference Between ASO and LRM/SNODAS

Low SWE day (2015-04-09) | ASO: 114 mm

LRM: 103 mm



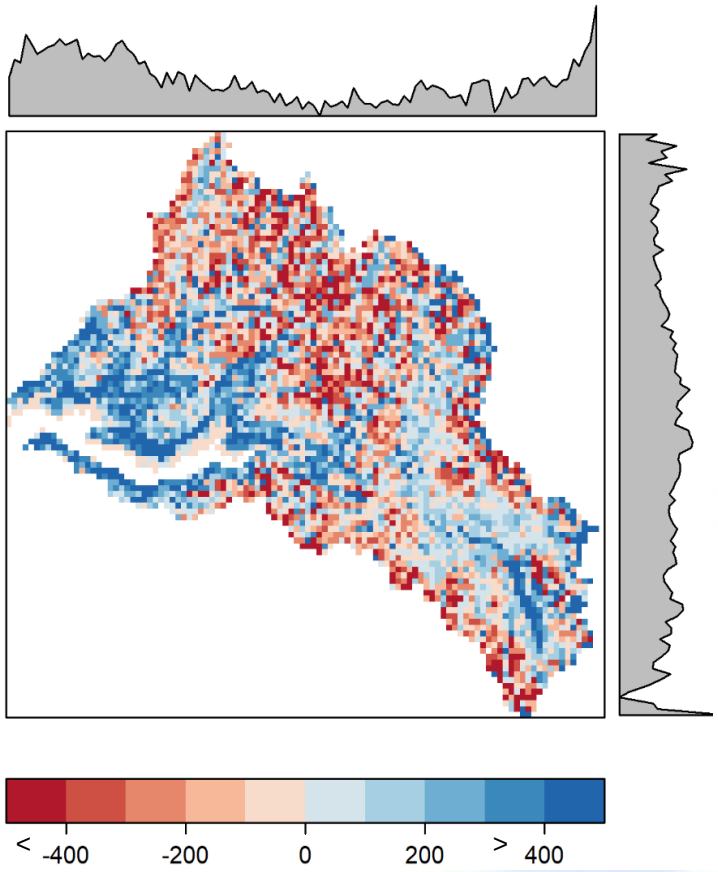
SNODAS: 197 mm

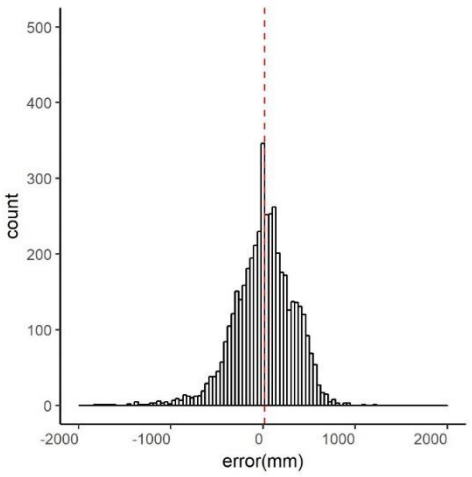


Difference Between ASO and LRM/SNODAS

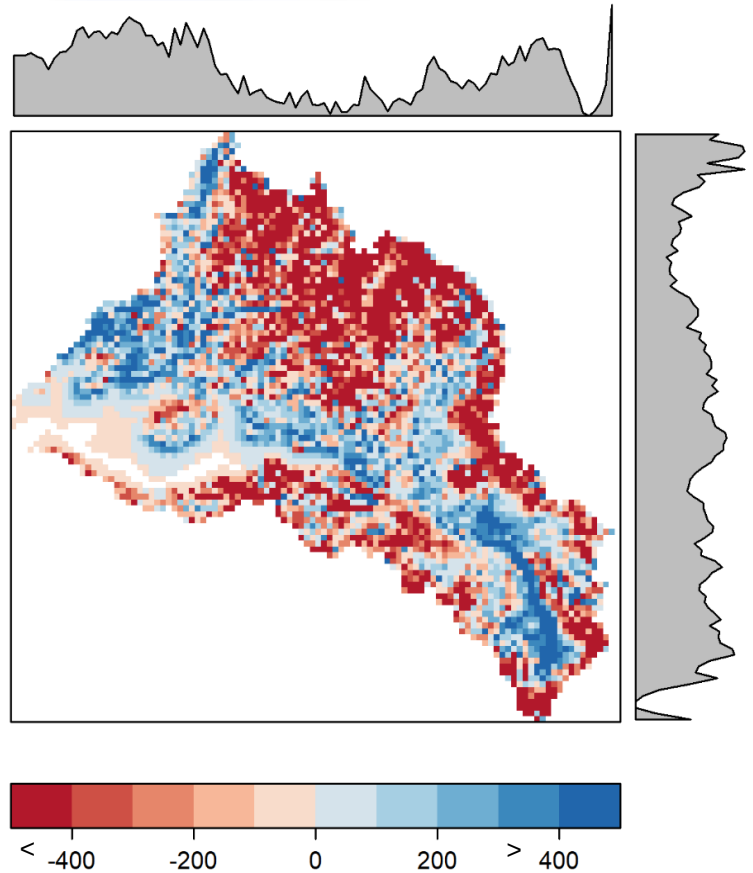
Average SWE day (2016-03-26) | ASO: 720 mm

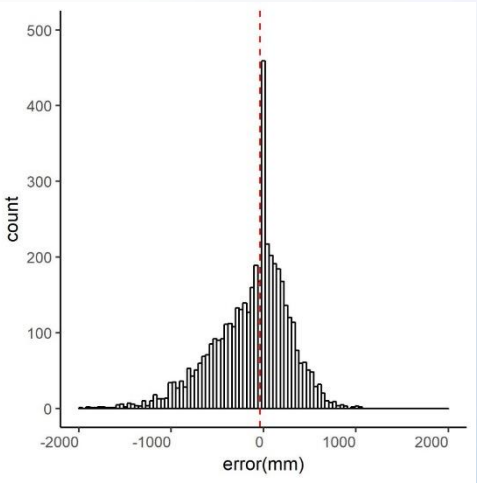
LRM: 737 mm





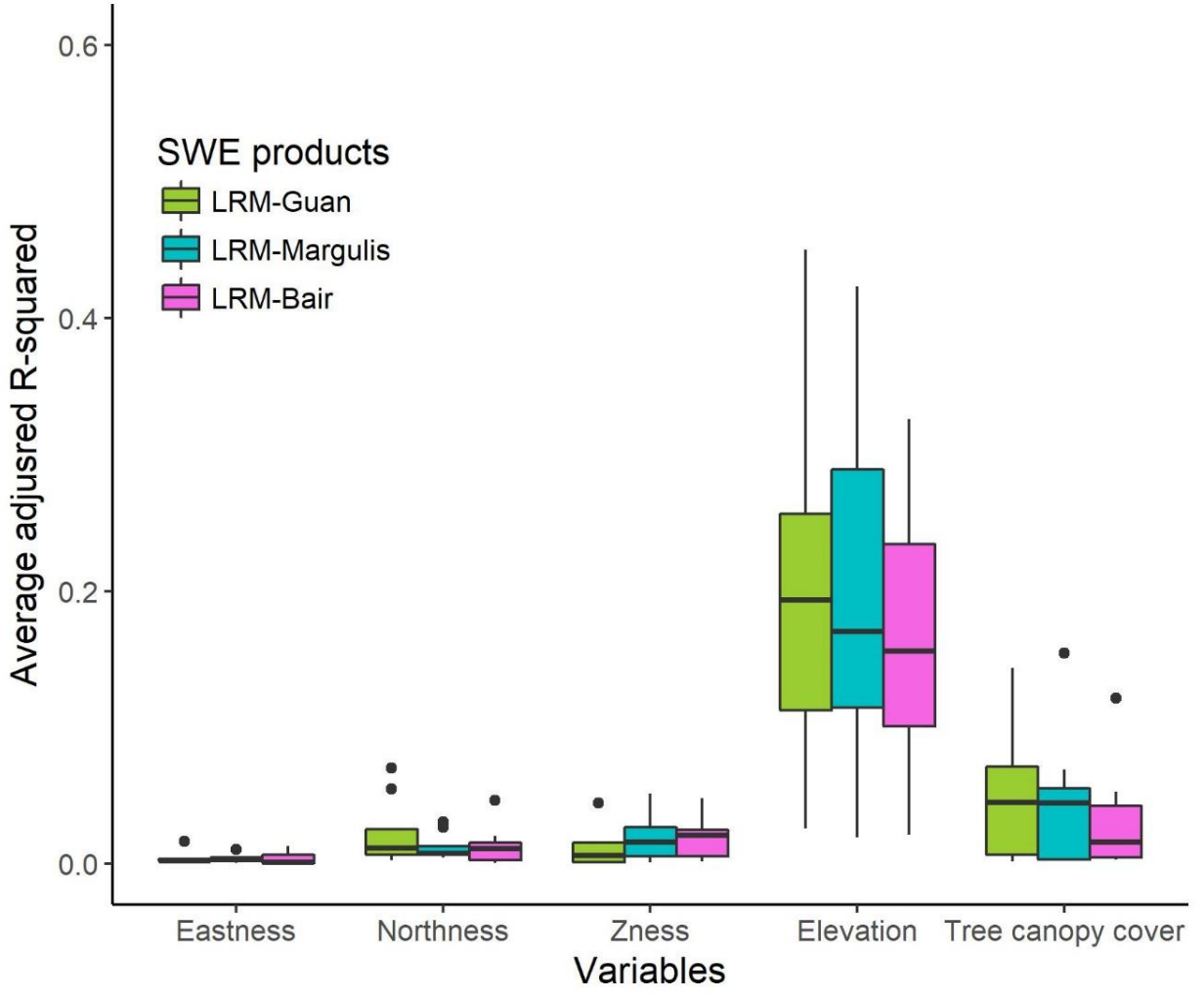
SNODAS: 590 mm





Using ASO to bias correct SWE estimates

- Correlate bias with terrain variables
- Highest correlation with Elevation
- Effects of forest cover an aspect are secondary



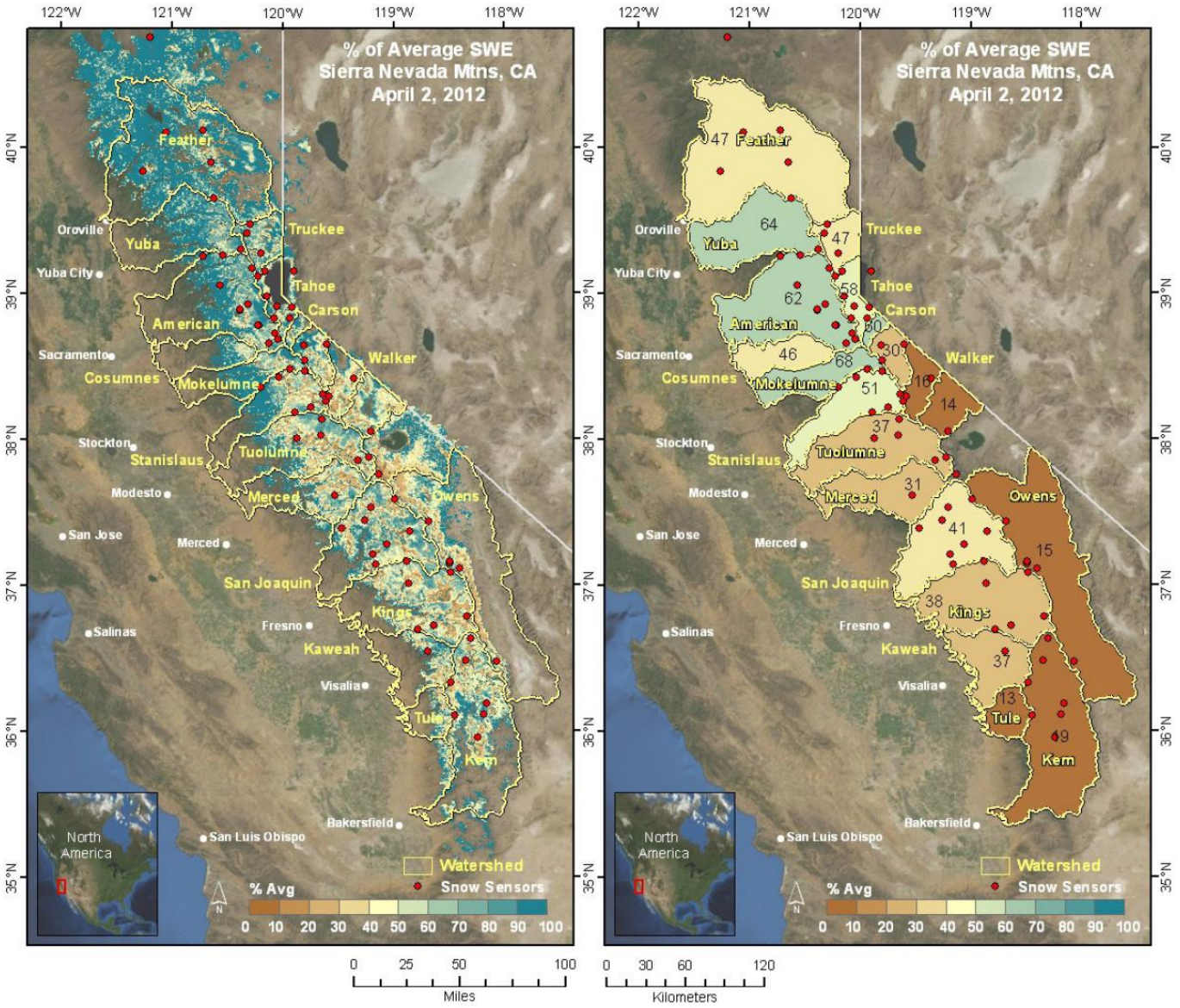
April 2012

April 2012 Snow Survey, Phillip's Station

California DWR

Subscribe 3,154

154 views



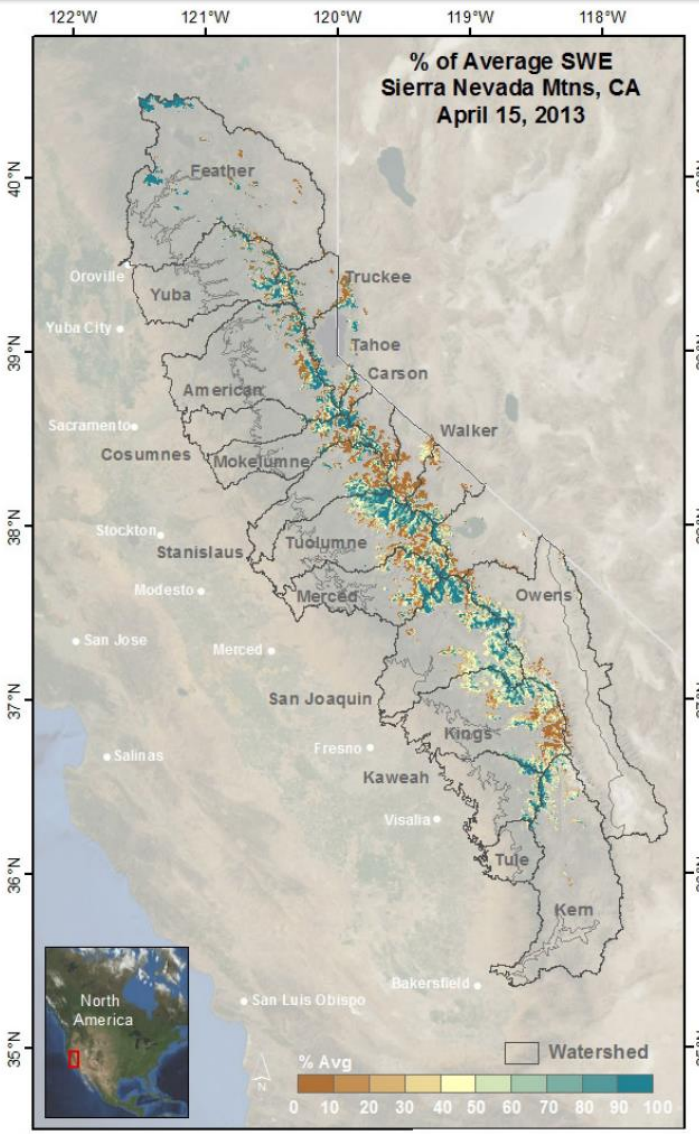
April 2013

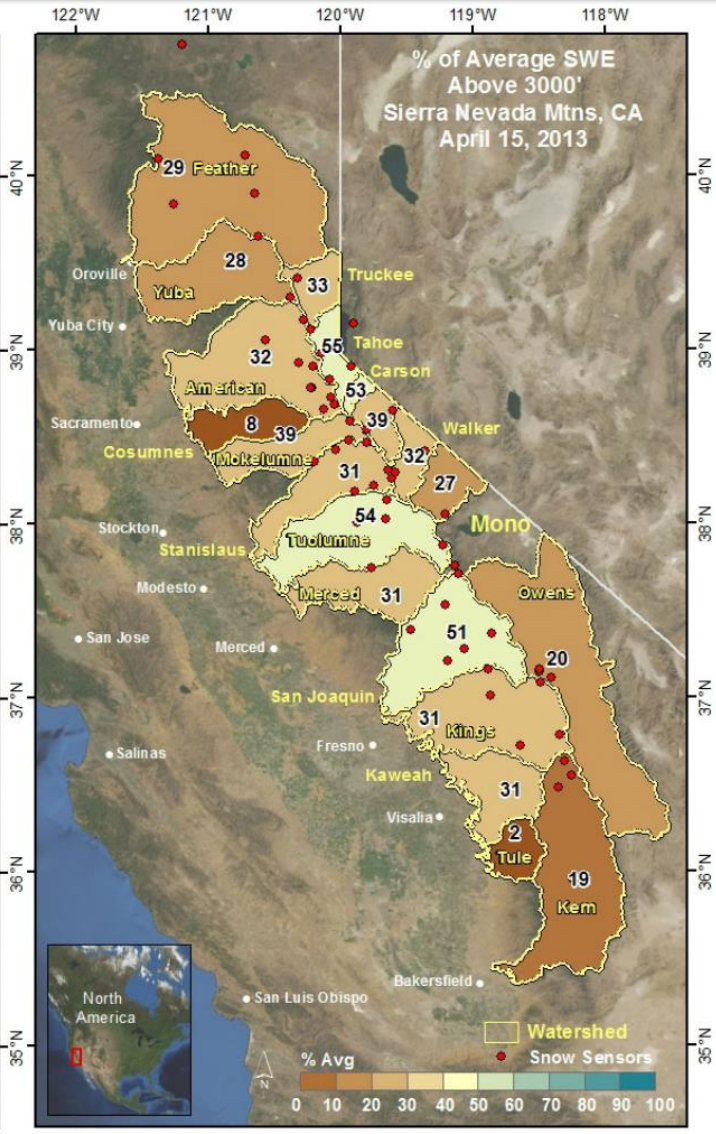
April 2013 Snow Survey, Phillip's Station

California DWR

Subscribe 3,154

108 views





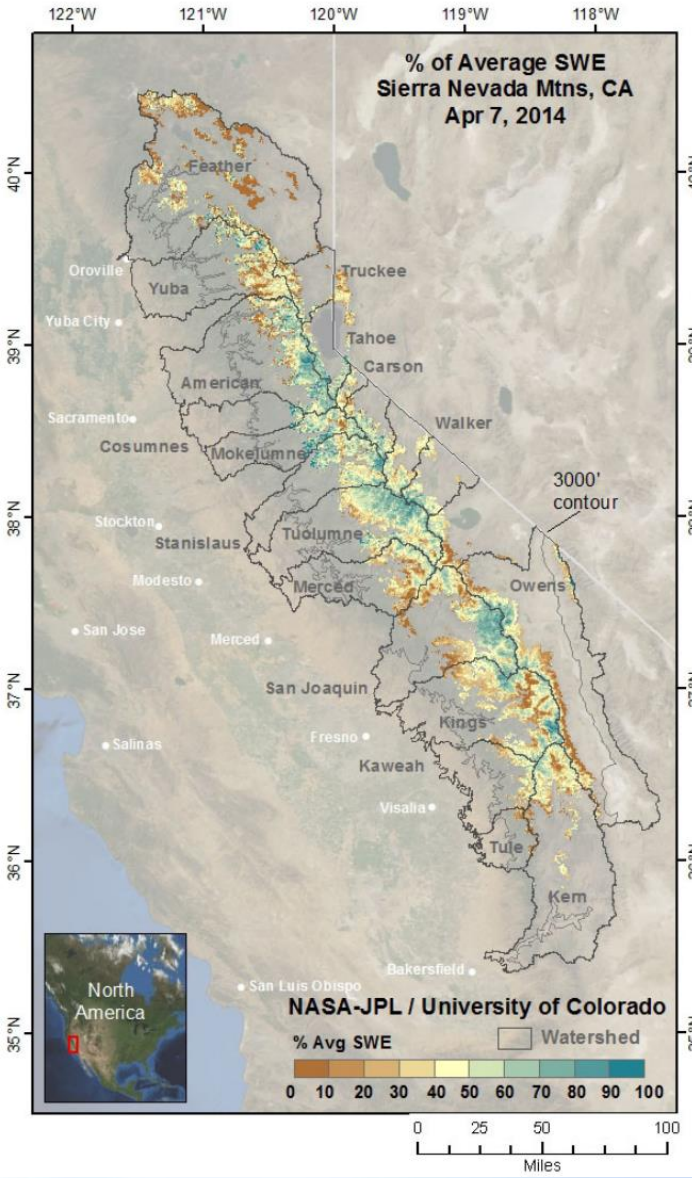
April 2014

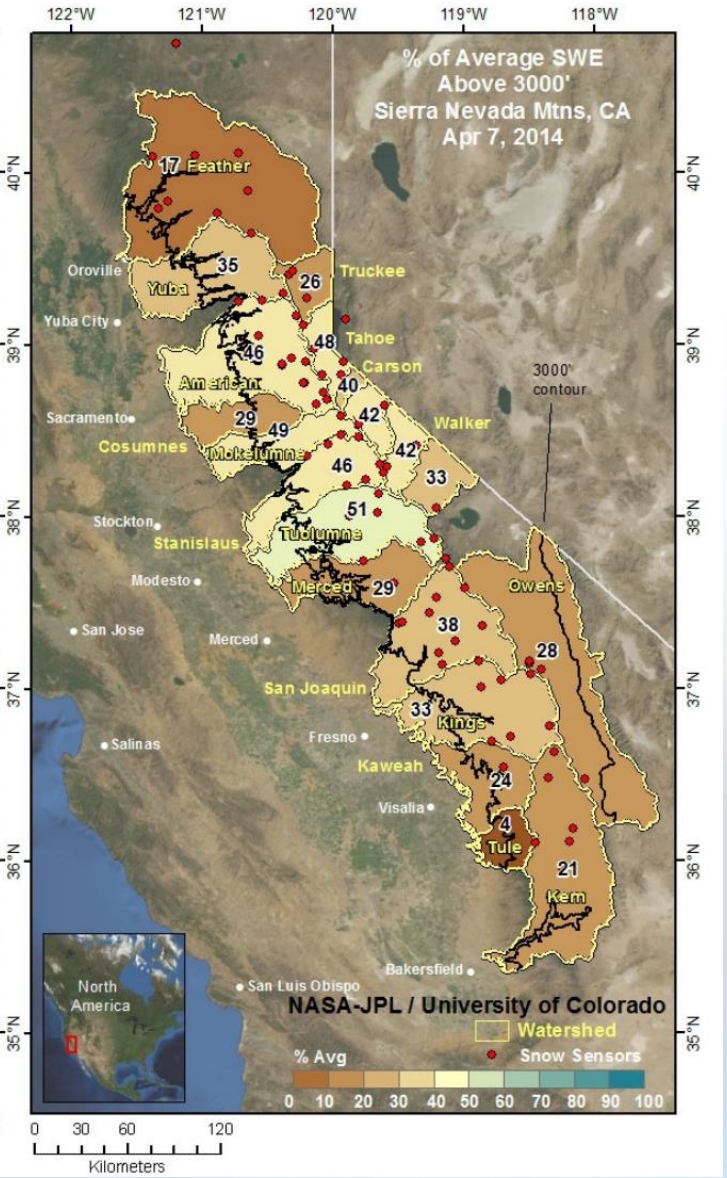
March 2014 Snow Survey, Phillip's Station

California DWR

Subscribe 3,154

316 views





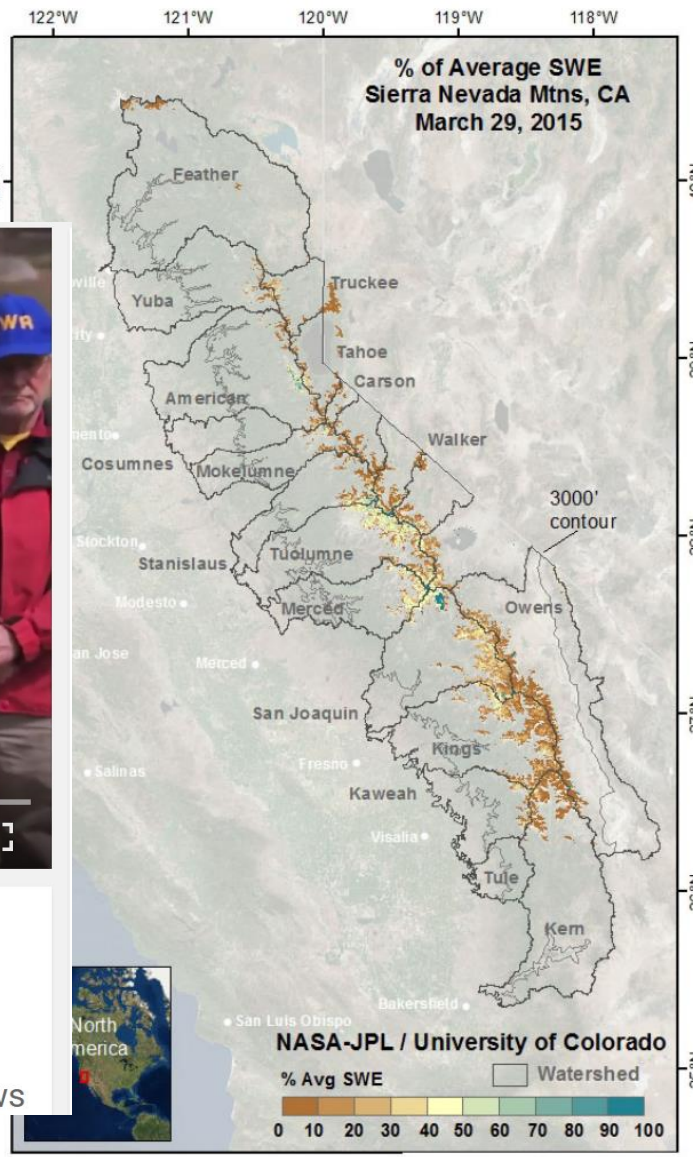
April 2015

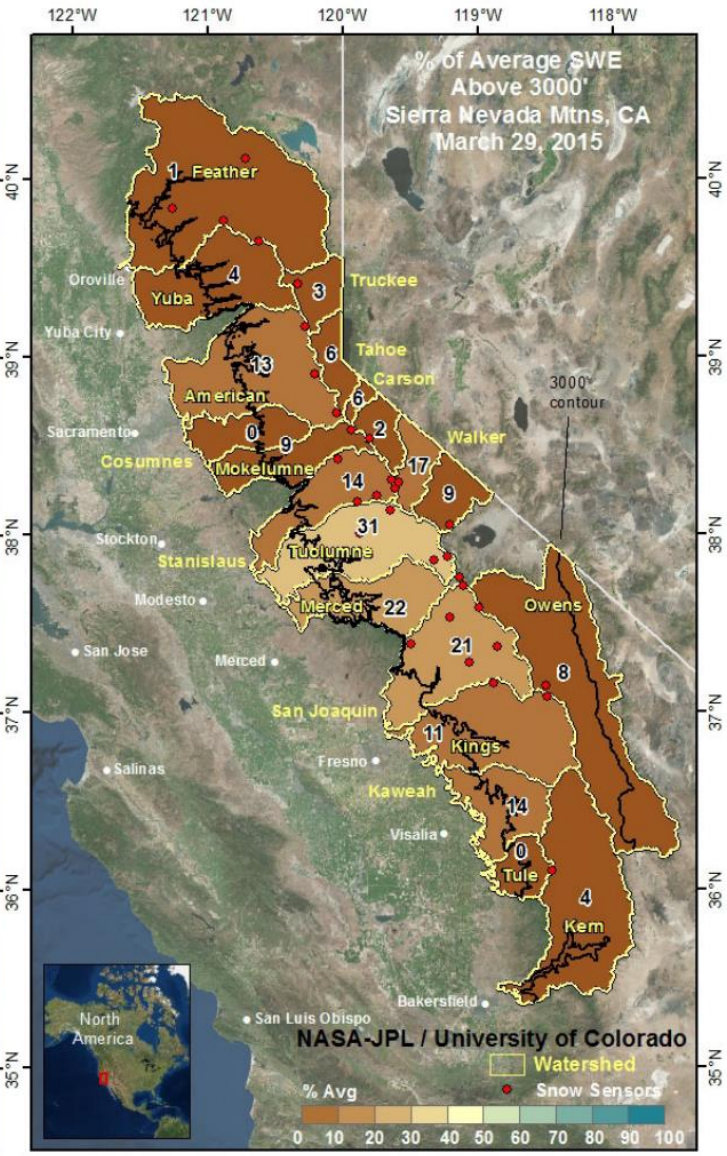
Governor Brown's Executive Order at the April 2015 Snow Survey, Phillip's Station

California DWR

Subscribe 3,154

2,940 views





April 2015

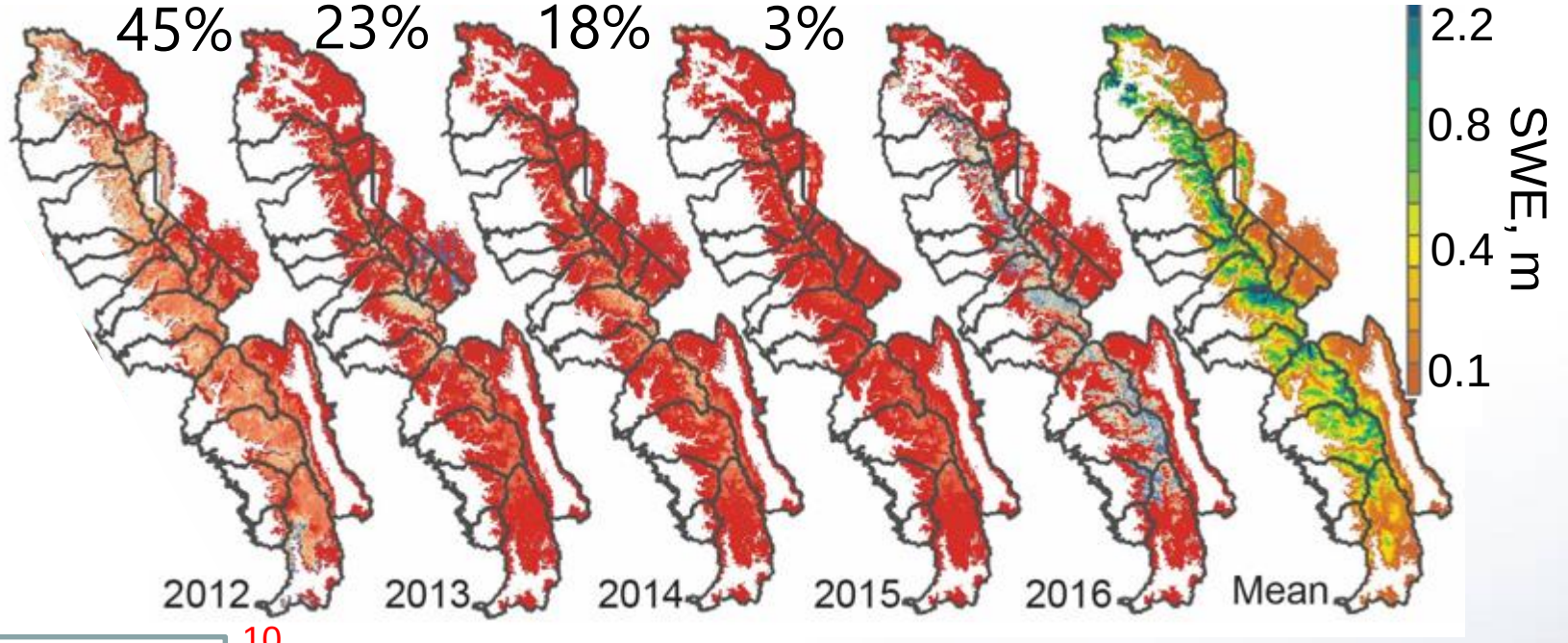
Governor Brown's Executive Order at the April 2015 Snow Survey, Phillip's Station

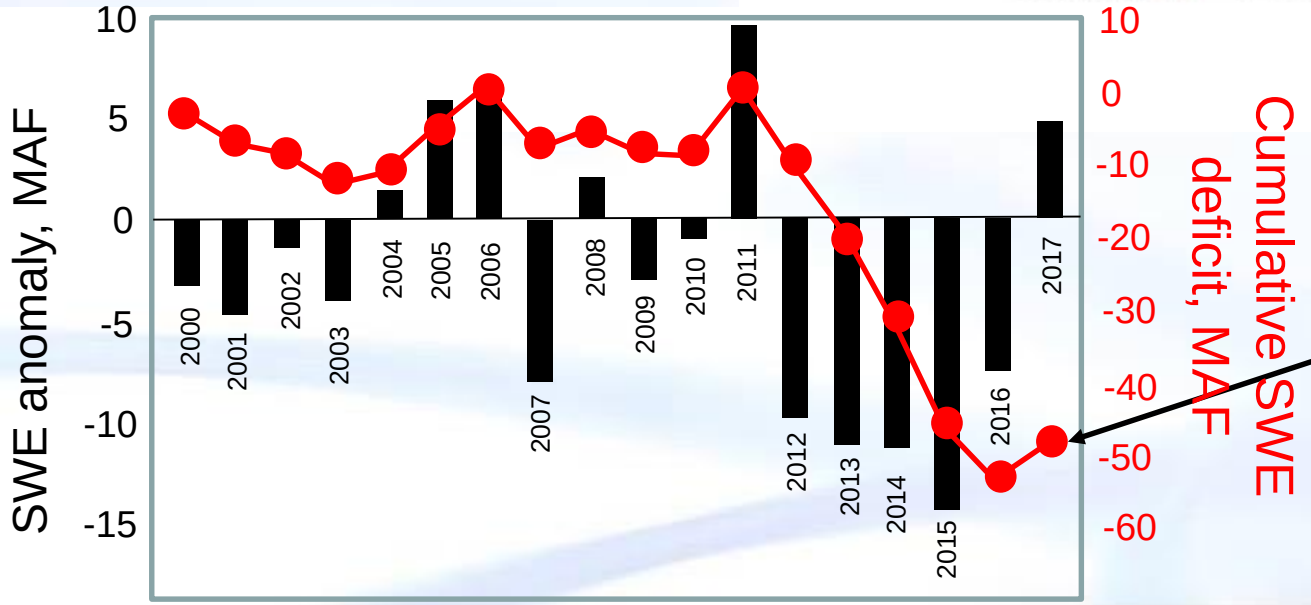
California DWR

Subscribe 3,154

2,940 views

SWE Estimates During the CA Drought

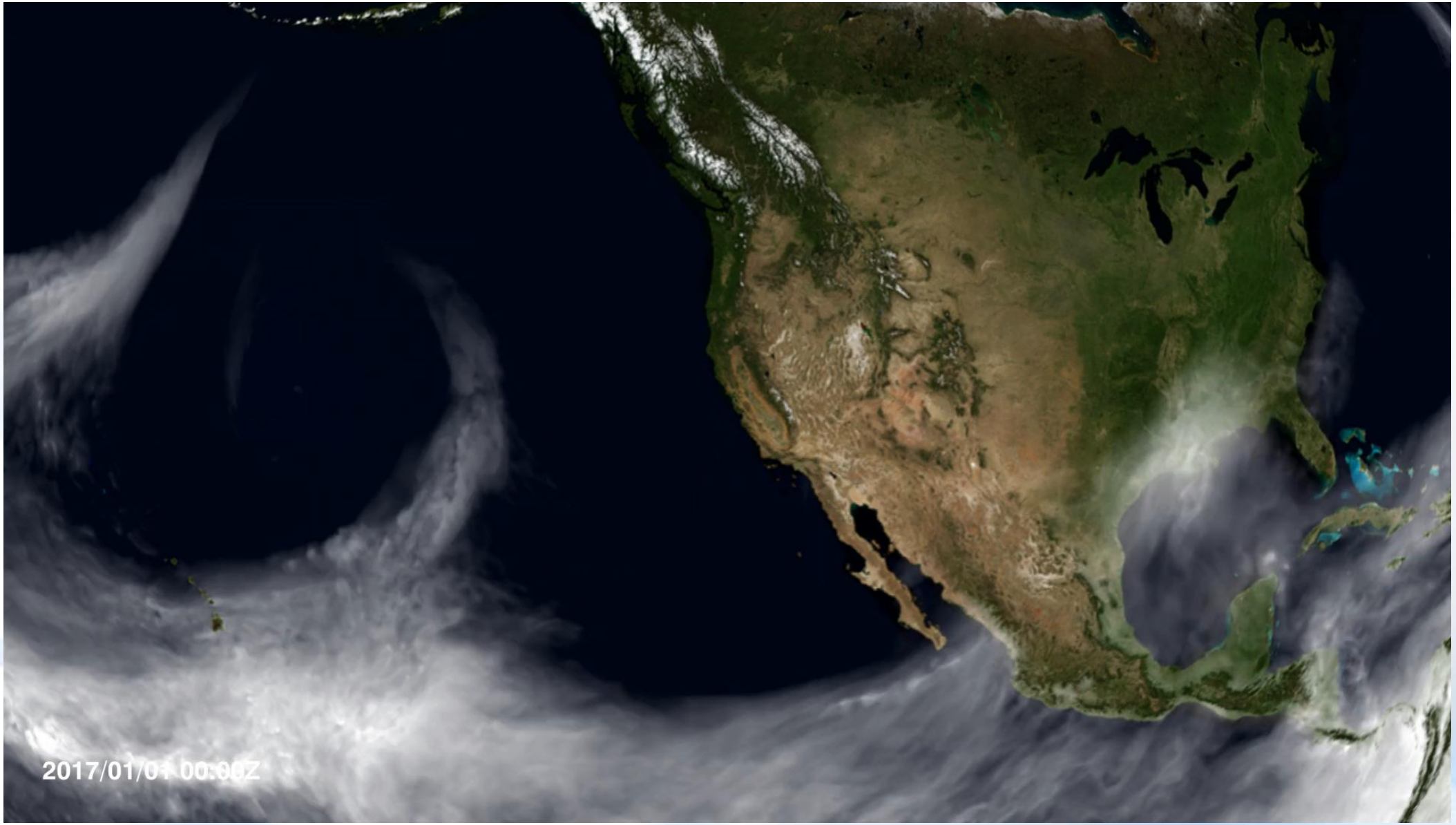




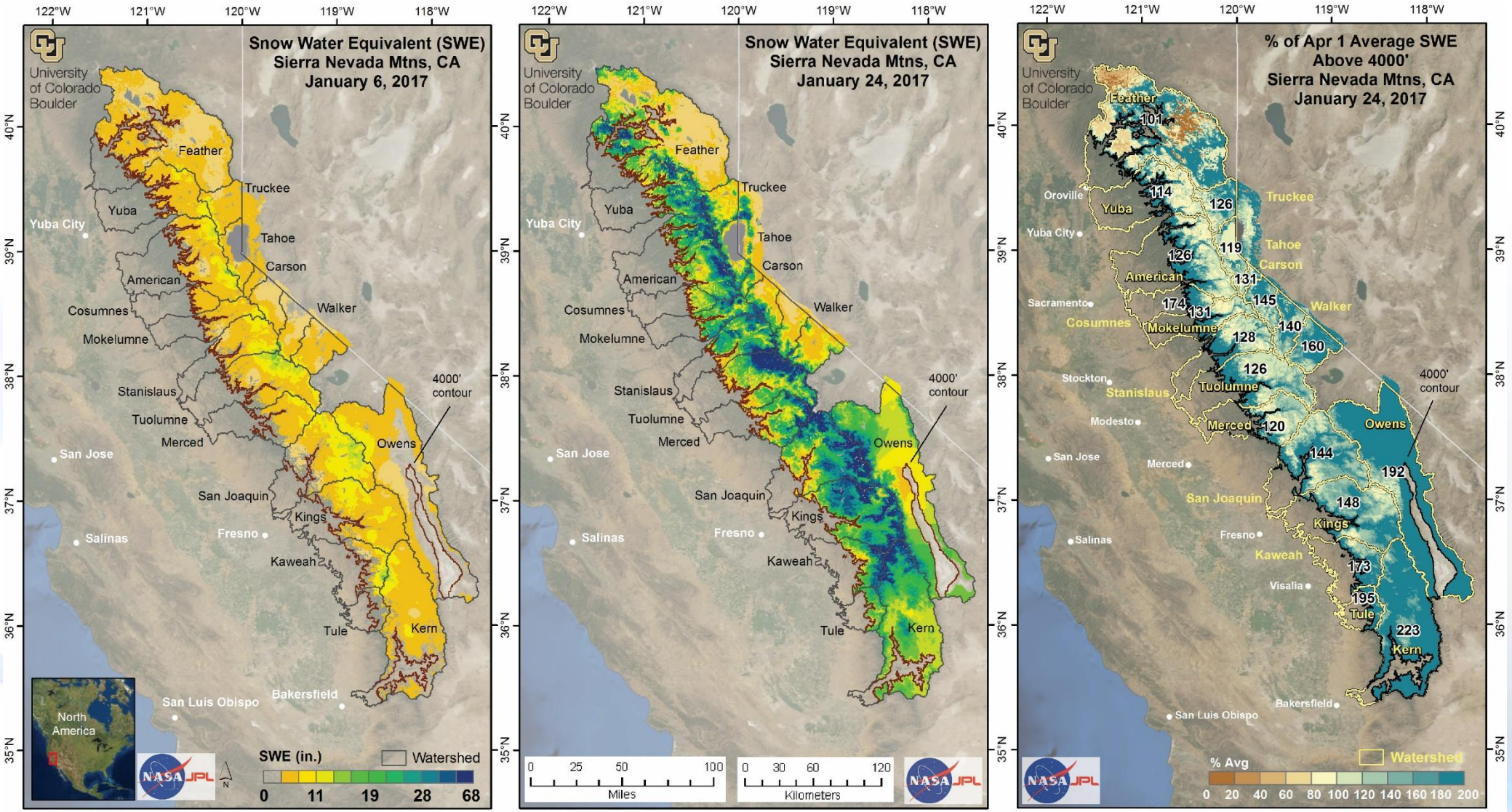
Deficit going into 2018 water year: 54 Million Acre Feet

Note: 2018 was also a very low snow year.

2017 & The End of the Drought?



How can remotely sensed SWE information improve flood forecasts?



Drought or Flood: What to tell the press?

SFGATE LOCAL NEWS SPORTS BUSINESS A&E FOOD LIVING TRAVEL REAL ESTATE

Even after epic storms, groundwater still depleted by drought

By Peter Fimrite, San Francisco Chronicle Updated 5:36 pm, Monday, January 30, 2017

ctions The Washington Post Sign In Su

Capital Weather Gang

It snowed 5.7 trillion gallons of water in California this January

By Jason Samenow January 30

SECTIONS SEARCH Los Angeles Times

ONDAY FEB. 20, 2017 MOST POPULAR LOCAL SPORTS ENTERTAINMENT POLITICS OPINION PLACE AN AD

January storms erase part of California's snowpack deficit

Heavy Rainfall and Full Reservoirs: Does SWE matter?

From: Anderson, Michael L.@DWR [mailto:Michael.L.Anderson@water.ca.gov]
Sent: Wednesday, January 25, 2017 5:55 PM
To: Noah Paul Molotch <Noah.Molotch@colorado.edu>
Subject: Re: map of SWE anomaly for press release

Hi Noah

Read your press release. Some things to note are that we can have floods during droughts due to the nature of atmospheric river events so notion of floods as the opposite of Drought isn't a good model for CA. Also rain on snow in a deep pack is different than a shallow pack so would resist the scare statement of rain on snow causing catastrophic flooding. Elevated flood risk now due more to limited surface reservoir space than melting snow with the AR based rain. AR based rain enough of a problem on its own. Thanks for working on this. I appreciate the help in characterizing the impact of these storms

Mike

Heavy Rainfall and Full Reservoirs: Does SWE matter?

Wed 1/25/2017 6:14 PM

Noah Paul Molotch

RE: map of SWE anomaly for press release

To 'Anderson, Michael L.@DWR'

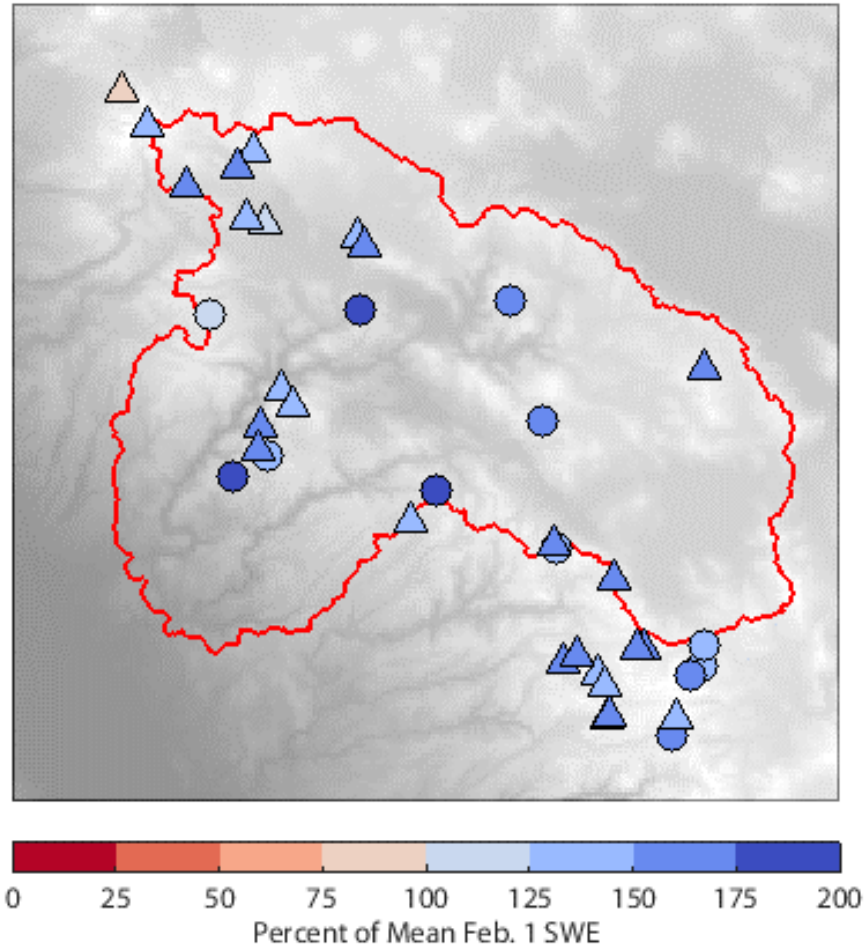
Also, and I pulled this out of the press release, but it is worth noting that I agree RE a deep snowpack being able to buffer a rain event. That said, and what I was referring to, is that we have a lot of relatively shallow snow at lower elevation (that is anomalous) and given the large land area covered by this snow, if we get another very intense AR and it comes as rain, the rain-on-snow could be an important aspect of flood risk (I didn't say "catastrophic"). Anyway, just want to make sure DWR realizes that this risk may be greater right now because of the abnormal low elevation snow storage. We need more research on rain-on-snow; maybe we should discuss this in the context of our collaboration?

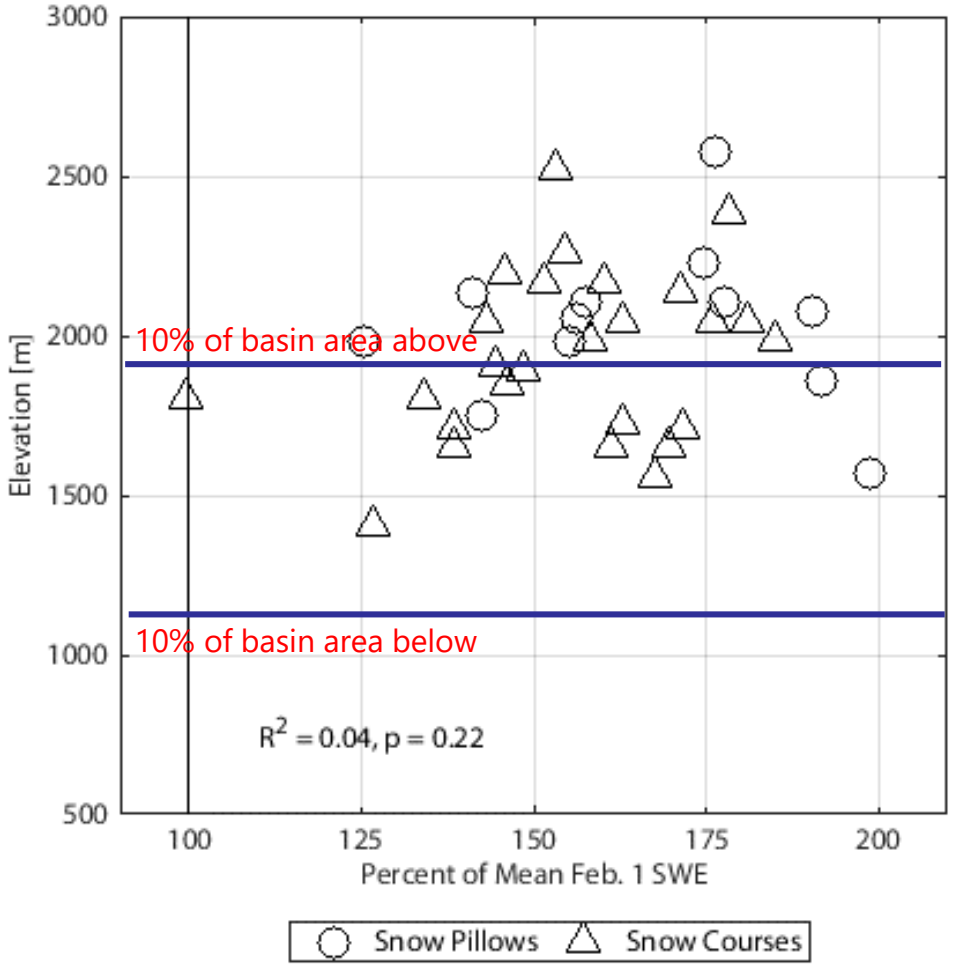
Cheers, Noah

Oroville Disaster: Rain-on-Snow?

- Largest storage facility in CA State Water Project.
- Damage: 45 feet deep, 300 feet wide, and 500 feet long.
- ~$200 Million Damage
- 188,000 People evacuated

Antecedent Snowpack

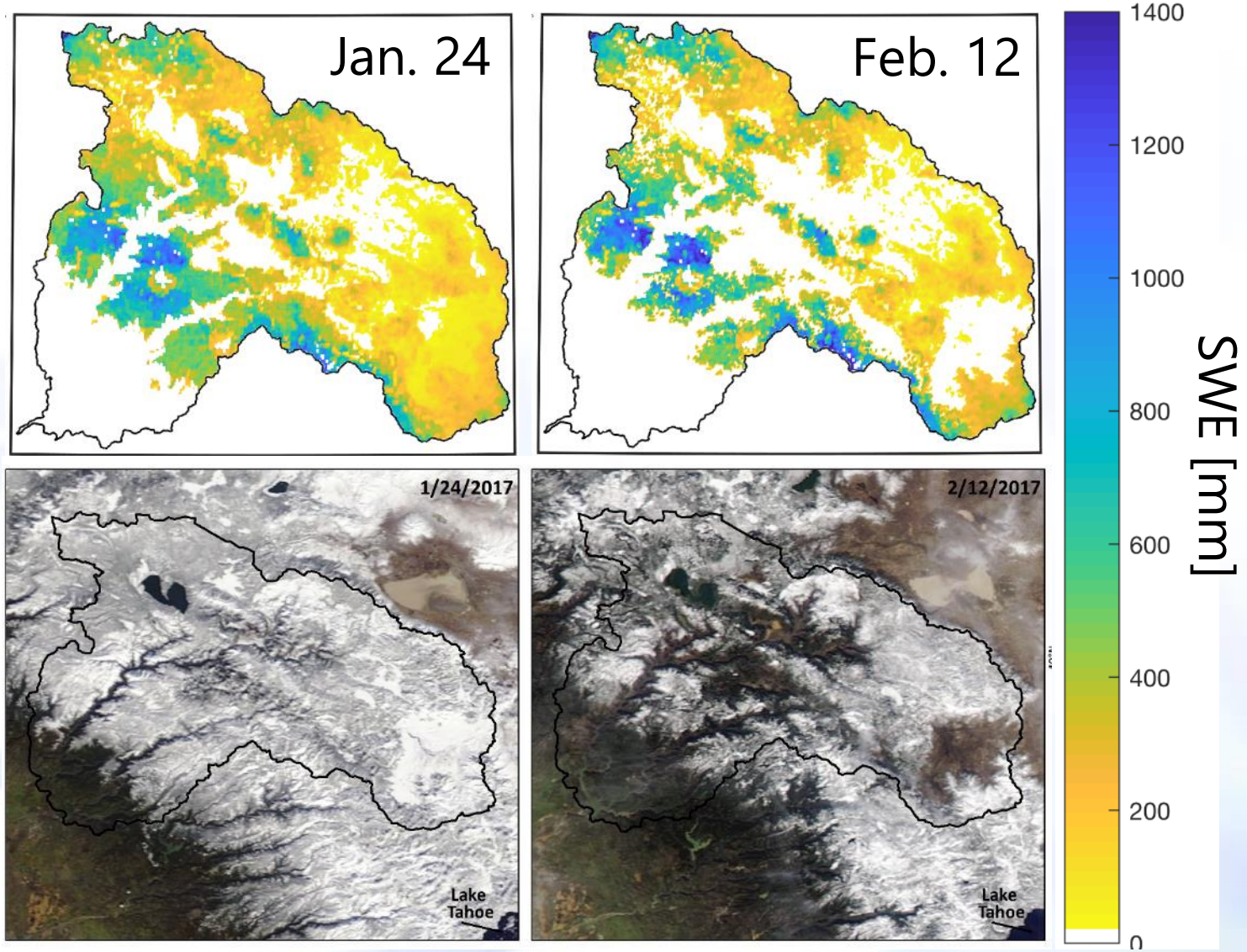




- Antecedent snowpack far above February 1 long-term average (160% of normal) after very active AR sequence in January
- SWE above average at all elevations with pillows/courses

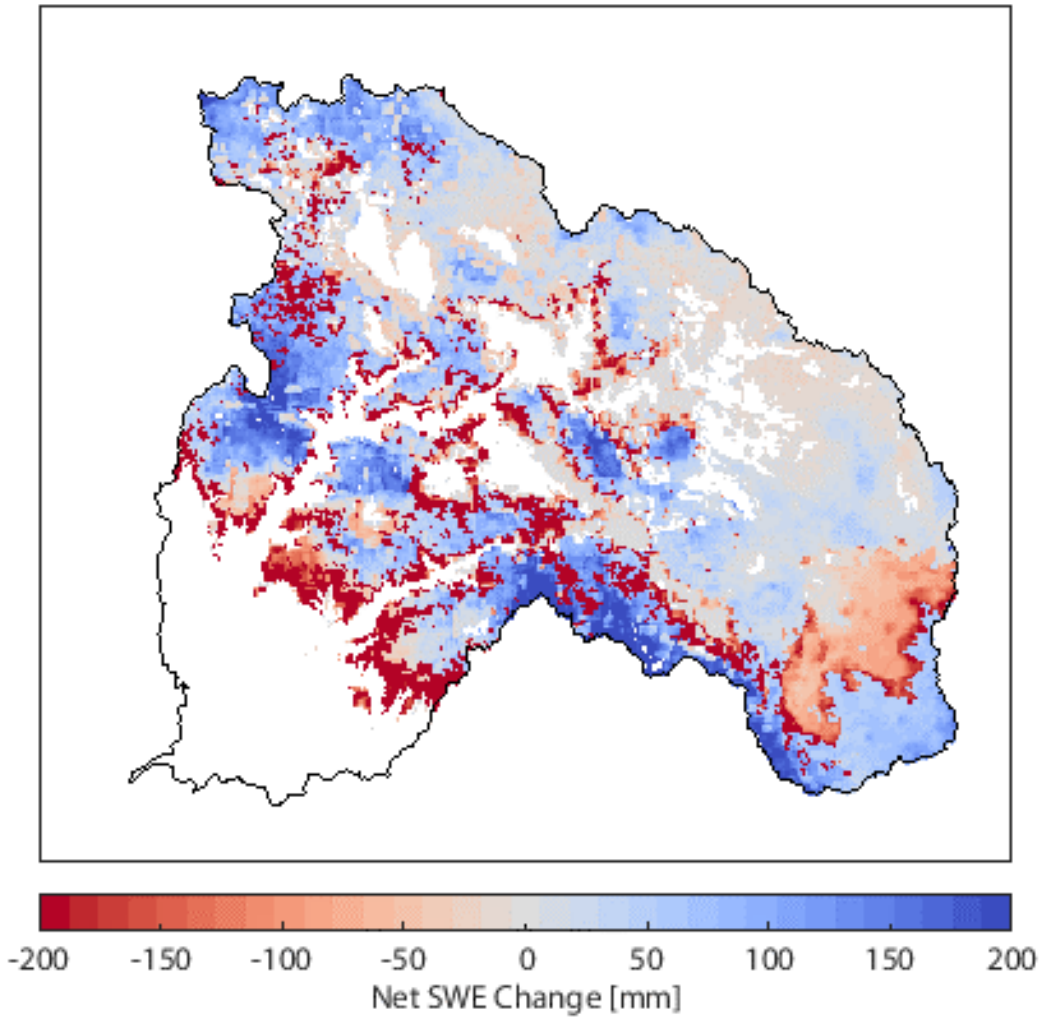
Henn, Musselman, Ralph, Lestak, and Molotch (*in prep*)

SWE maps before and after the flood event show significant snowmelt



- CU / JPL gridded SWE estimates before & after the flood event
- MODIS clear-sky images on January 24 and February 12, 2017 show snow loss.

Basin-wide snowpack losses contributed 11% to the flood wave: CU/JPL SWE Product



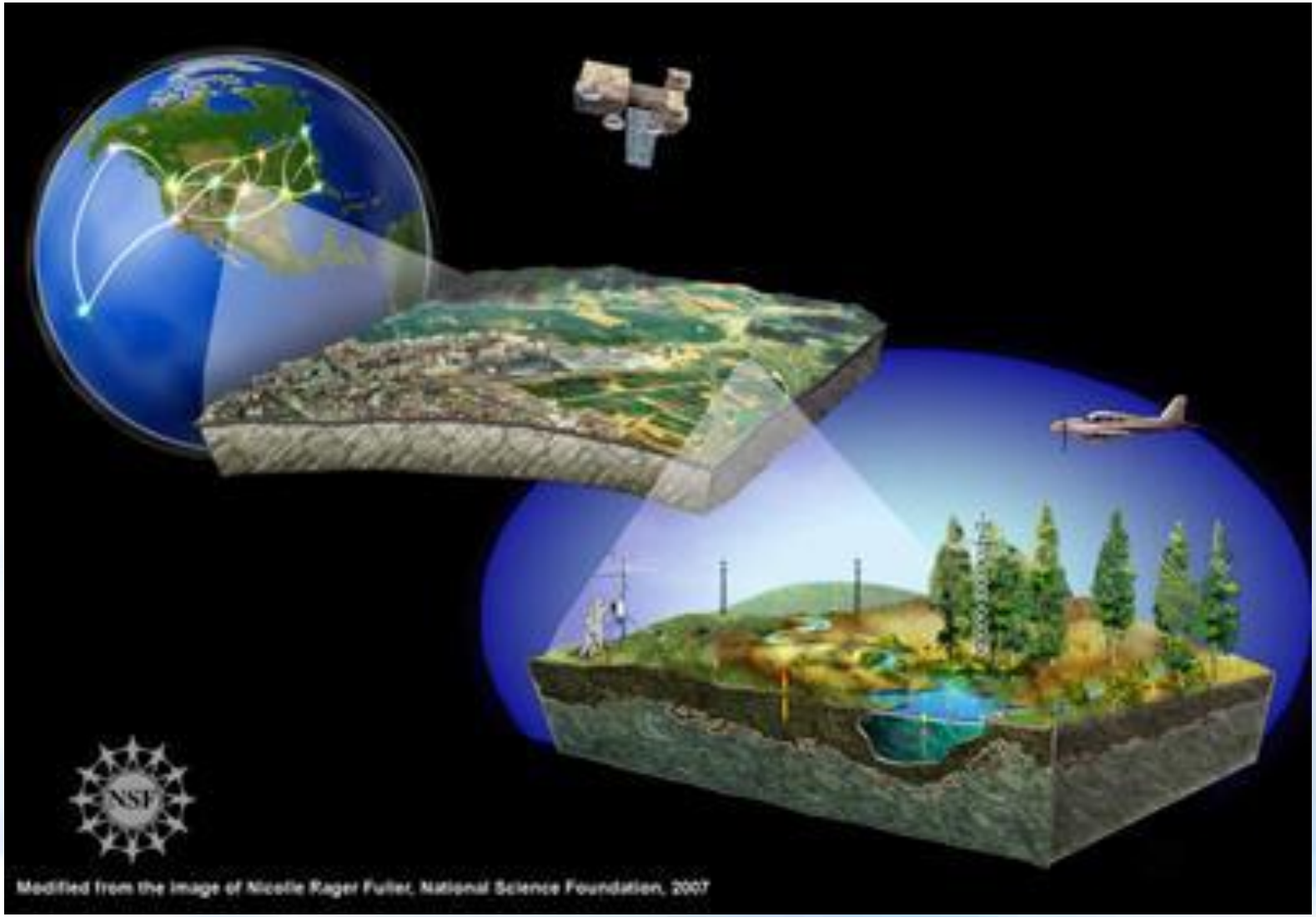
- 1.02 in. SWE loss averaged over Feather River Basin between Jan. 24 and Feb. 12
- 9 in measured precipitation over basin
- total water available for streamflow generation was 11% higher due to snowmelt

Henn, Musselman, Ralph, Lestak, and Molotch (*in prep*)

An integrated SWE observing system

Merging satellite data with airborne and ground data to estimate SWE

- Ground data:
  - Truth
  - Long record
  - Limited in space
- Airborne data:
  - Accurate
  - High resolution
  - Limited in extent and frequency ($$)
- Satellite data
  - Large extent
  - Frequent sampling
  - Limited in resolution and accuracy



How can remotely sensed SWE information improve water supply forecasts?

CONCLUSIONS

- Flood risk assessment: real time SWE mapping illustrates that 11% of the Oroville-event flood wave was associated with snowmelt / rain-on-snow
- Drought impact assessment: SWE products show a snow-water deficit of 54 Million Acre Feet going into the 2018 water year
- Integrated measurement approach is imperative for water resources sustainability.
- California MUST lead the way……